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Graft-Versus-Host Disease Amelioration by Human Bone Marrow Mesenchymal Stromal/Stem Cell-Derived Extracellular Vesicles Is Associated with Peripheral Preservation of Naive T Cell Populations

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Graft-Versus-Host Disease Amelioration by Human Bone Marrow Mesenchymal Stromal/Stem Cell-Derived Extracellular Vesicles Is Associated with Peripheral Preservation of Naive T Cell Populations

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Key Words. Mesenchymal stem cells • Graft-versus-host disease • Extracellular vesicles • microRNA • Regulatory T cells • Naive T cells • Hematopoietic stem cell transplantation

ABSTRACT

A substantial proportion of patients with acute graft-versus-host disease (aGVHD) respond to cell therapy with culture-expanded human bone marrow mesenchymal stromal/stem cells (BM-MSCs). However, the mechanisms by which these cells can ameliorate aGVHD-associated complications remain to be clarified. We show here that BM-MSC-derived extracellular vesicles (EVs) recapitulated the therapeutic effects of BM-MSCs against aGVHD. Systemic infusion of human BM-MSC-derived EVs prolonged the survival of mice with aGVHD and reduced the pathologic damage in multiple GVHD-targeted organs. In EV-treated GVHD mice, CD4⁺ and CD8⁺ T cells were suppressed. Importantly, the ratio of CD62L-CD44⁺ to CD62L⁺ + CD44⁺ T cells was decreased, suggesting that BM-MSC-derived EVs suppressed the functional differentiation of T cells from a naive to an effector phenotype. BM-MSC-derived EVs also preserved CD4⁺ + CD25⁺ + Foxp3⁺ regulatory T cell populations. In a culture of CD3/CD28-stimulated human peripheral blood mononuclear cells with BM-MSC-derived EVs, CD3⁺ T cell activation was suppressed. However, these cells were not suppressed in cultures with EVs derived from normal human dermal fibroblasts (NHDFs). NHDF-derived EVs did not ameliorate the clinical or pathological characteristics of aGVHD in mice, suggesting an immunoregulatory function unique to BM-MSC-derived EVs. Microarray analysis of microRNAs in BM-MSC-derived EVs versus NHDF-derived EVs showed upregulation of miR-125a-3p and downregulation of cell proliferative processes, as identified by Gene Ontology enrichment analysis. Collectively, our findings provide the first evidence that amelioration of aGVHD by therapeutic infusion of BM-MSC-derived EVs is associated with the preservation of circulating naive T cells, possibly due to the unique microRNA profiles of BM-MSC-derived EVs. *STEM CELLS* 2018;36:434–445

SIGNIFICANCE STATEMENT

Cell therapy with human bone marrow mesenchymal stromal/stem cells (BM-MSCs) is clinically effective for patients with intractable acute graft-versus-host disease (aGVHD) after allogeneic hematopoietic stem cell transplantation. This study revealed that BM-MSC-derived extracellular vesicles (EVs) recapitulated the therapeutic effects of BM-MSCs against aGVHD by inhibiting effector T cell induction and preserving peripheral naive T cells. Gene Ontology analysis of microRNAs differentially expressed in BM-MSC-derived EVs suggested that these microRNAs may downregulate cell proliferative processes. These findings suggest that BM-MSC-derived EVs mediate the anti-aGVHD effects of BM-MSCs, thereby raising the possibility of using EVs as a cell-free therapy for the treatment of aGVHD.

INTRODUCTION

Although molecularly-targeted therapies have improved the prognosis of patients with hematological diseases, allogeneic hematopoietic stem cell transplantation (HSCT) remains the only

curative therapy for refractory disease. Acute graft-versus-host disease (GVHD) occurs when immune cells transplanted from a genetically non-identical donor recognize and are activated by alloantigens in HSCT recipients, resulting in

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organ damage [1]. Various immunosuppressants have been clinically applied for the prevention of acute GVHD [2]. However, a substantial proportion of HSCT recipients develop this potentially life-threatening complication. The efficacy of standard primary therapy with corticosteroids is about 50%, and the complete response rate to secondary therapy with a variety of immunosuppressants is about 30%, with a median overall survival of less than 1 year in steroid-refractory patients [3]. Therefore, development of novel treatment strategies is extremely important to improve the overall survival of recipients of HSCT.

Human mesenchymal stromal/stem cells (MSCs) are multipotent cells that show a variety of biological characteristics, including immunomodulatory capacity [4–6]. Clinical studies have demonstrated the efficacy of systemic infusion of culture-expanded allogeneic human bone marrow (BM)-MSCs for the treatment of patients with steroid-refractory acute GVHD [7]. In some countries, allogeneic bone marrow mesenchymal stromal/stem cell (BM-MSC) products are clinically used as an off-the-shelf product for steroid-resistant acute GVHD [8]. Previous lines of evidence have suggested that BM-MSCs inhibit the function of immune cells mainly through the local secretion of soluble immune modulators and partially through cell-to-cell contact-dependent mechanisms [9]. However, because most infused BM-MSCs remain in the lungs, these observations do not clearly explain the mechanism by which MSCs can exert “remote” immunomodulatory effects in GVHD-affected organs.

Recently, extracellular vesicles (EVs) have gained interest as mediators of cell-to-cell communication based on their ability to transmit signals to sites of action regardless of physiological barriers [10, 11]. EVs are small membrane particles released from many types of cells. They contain various types of molecules, including microRNAs that regulate a diverse range of biological processes [12]. Several studies have demonstrated that BM-MSC-derived EVs contribute to the immunomodulatory and regenerative effects of MSCs [13]. Most of these reports show that MSC-derived EVs can recapitulate the therapeutic and regenerative effects of MSCs on damaged tissues/organs in models of myocardial ischemia [14], acute tubular injury [15], stroke [16], acute lung injury/ischemia [17, 18], and skin wounds [19]. More recently, a case report described the successful treatment of a patient with refractory acute GVHD by intravenous infusions of EVs derived from BM-MSCs [20]. However, the biologic mechanisms by which BM-MSC-derived EVs exert these functions remain unknown.

In this study, we examined the effects of human BM-MSC-derived EVs on the clinical, pathological, and immunologic characteristics of acute GVHD model mice. A microarray analysis was also conducted to evaluate the biological processes mediated by microRNAs within human BM-MSC-derived EVs.

MATERIALS AND METHODS

Human BM-MSC Culture

Human MSCs were isolated from BM samples purchased from AllCells (Alameda, CA) using our previously published method [21, 22]. BM samples were obtained from three different healthy adult donors. A single-cell suspension of 1×10^6 BM mononuclear cells was seeded into a 15 cm culture dish, and adherent cells were cultured in Advanced Minimal Essential

Medium (Invitrogen/Thermo Fisher Scientific, Waltham, MA) supplemented with 5% fetal bovine serum (FBS; Gibco/Thermo Fisher Scientific), 100 μ M ascorbic acid (Wako Pure Chemical Industries, Osaka, Japan), 2 mM L-glutamine, 100 U/ml penicillin, and 100 μ g/ml streptomycin (all from Gibco/Thermo Fisher Scientific) (complete culture medium, CCM). Primary cultures were passaged to disperse the colony-forming cells (passage 1). Cells at passage 3 were used as BM-MSCs in this study. Prior to use in experiments, surface marker expression profiles of these cells were obtained to confirm that the cells fulfil the minimal definition criteria for human MSCs, as proposed by the International Society for Cellular Therapy [23]. In addition, the multilineage differentiation capacity and hematopoiesis-inducing capacity of these cells were confirmed as previously described [24, 25]. In some experiments, normal human dermal fibroblasts (NHDFs) purchased from Lonza (Basel, Switzerland) were cultured using the FGM-2 Bulk Kit (Lonza), which contains human fibroblast growth factor- β , insulin, FBS, and gentamicin/amphotericin-B.

EV Preparation

Human BM-MSCs (2×10^5 cells) were plated in T-75 culture flasks in CCM. Seven days later, the CCM was replaced with 10 ml serum-free medium (SFM). The conditioned SFM was collected after 24 hours and centrifuged at 2,000g for 30 minutes. The supernatant fraction was passed through a 0.2 μ m filter, mixed with Total Exosome Isolation Reagent (Invitrogen/Thermo Fisher Scientific), incubated overnight at 4°C, and centrifuged at 10,000g for 1 hour. The EV-containing pellet was resuspended in Dulbecco's phosphate-buffered saline at 100 μ l per 1.0×10^6 BM-MSCs. The particle and protein contents of the EVs were measured by tunable resistive pulse sensing (qNano, Izon Science Ltd, Oxford, U.K.) [26] or by Bradford protein assay (Thermo Fisher Scientific), respectively. The mean protein and particle contents of the EV preparations were 4.48 mg/ml and 4.23×10^9 particles/ml, respectively.

Immunoblot Analysis and Transmission Electron Microscopy

For immunoblot analysis, EVs solutions were lysed with 5X SDS sample buffer, separated on 4%–12% SDS-PAGE gels (Invitrogen/Thermo Fisher Scientific), and transferred to PVDF membranes. Primary antibodies against CD63 (clone TS63, Abcam, London, U.K.) and CD81 (rabbit polyclonal, System Biosciences, Palo Alto, CA) were used to detect EVs. For transmission electron microscopy, EVs were placed on formvar-coated copper grids and allowed to absorb onto the grid overnight. After the excess solution was carefully removed using filter paper, the samples were stained with 1% uranyl acetate for 10 minutes, dried, and observed with a JEOL JEM-1230S transmission electron microscope operating at 80 KV (JEOL, Tokyo, Japan).

In Vitro T Cell Expansion Assay

Human peripheral blood mononuclear cells (PBMCs) were separated using Ficoll-Paque Plus (GE Healthcare Japan, Tokyo, Japan). PBMCs (1×10^6 /well) were activated with anti-CD3 and anti-CD28 antibodies using Human T-Activator CD3/CD28 Dynabeads (Life Technologies/Thermo Fisher Scientific) in 24-

well plates (25 μ l/well) according to the manufacturer's instructions (day 0). Five days later (day 5), the number of cells was counted by Trypan blue dye exclusion and their surface marker expression was assessed by flow cytometry. For co-culture assays, BM-MSCs (5×10^4 /well) were prepared in 24-well plates the day before adding the PBMCs (day -1). To examine the effects of EVs, 5 μ l EVs prepared from conditioned SFM derived from 5×10^4 BM-MSCs was added to the T cell expansion culture.

Murine Acute GVHD Model

Specific pathogen-free 7- to 9-week-old C57BL/6 mice (H-2D^b), DBA/2 mice (H-2D^d), and B6D2F1 mice (C57BL/6 \times DBA/2 F1; H-2D^{b \times d}) were obtained from CLEA Japan (Tokyo, Japan). For induction of GVHD, 1×10^7 spleen cells from parental C57BL/6 mice (B6) were intravenously injected via the tail vein into B6D2F1 (BDF1) mice that received 8 Gy total body irradiation prior to transplantation [27]. GVHD was indicated by a $\geq 10\%$ loss of body weight in the recipient mice [28]. The GVHD mice were randomized into two groups 5 days after the injection of the spleen cells. The control group received a tail vein injection of 200 μ l saline, and the EV-treated mice received an injection of 200 μ l saline containing EVs derived from 2×10^6 human BM-MSCs per kg of body weight; for example, for a mouse weighing 20 g, 4 μ l EVs derived from 4×10^4 human BM-MSCs were prepared and adjusted to a final volume of 200 μ l with saline (approximately 1.6×10^7 particles containing 16 μ g protein). The study was approved by the Committee for Animal Research of the Kyoto University Graduate School of Medicine (Medkyo #17284). All animal studies were performed in accordance with the relevant guidelines and regulations.

Histological and Clinical Assessment of GVHD

For histological assessment, mice were sacrificed 6 days after administration of EVs, and tissue samples from the large bowel, liver, small bowel, and skin were collected. The severity of GVHD was scored by evaluating H&E-stained paraffin-embedded sections of these tissues/organs, as previously described [29]. Seven (for the large and small bowel) or 10 (for the liver) parameters were evaluated and scored as follows: 0 (normal), 0.5 (rare, focal), 1 (mild, focal), 2 (mild, diffuse), 3 (moderate, diffuse), or 4 (severe, diffuse). Scores from each parameter were summed for a total score of 0–28 for the large bowel and small bowel, and 0–40 for the liver. For evaluation of the skin, the severity of damage was evaluated as mild, moderate, or severe by previously described criteria, with some modifications [30]. Clinical assessment was performed 10 days after the injection of spleen cells and was based on five parameters, including weight loss, posture, activity, fur texture, and skin integrity, as previously described [28, 31]. A score of 0 (good) to 2 (poor) for each parameter was summed, for a total score of 0–10.

Flow Cytometric Analysis

For the analysis of surface marker expression of BM-MSCs, NHDFs, and murine peripheral blood (PB), a single-cell suspension of these cells was stained with fluorescent-conjugated antibodies and analyzed on a FACS Canto II (BD Biosciences, Franklin Lakes, NJ). For the analysis of expanded cells in anti-CD3/CD28-stimulated human PBMC cultures, the Dynabeads were removed

with a magnet prior to staining. The primary antibodies used in this study are listed in Supporting Information Table S1. Dead cells were excluded by staining with propidium iodide. For the staining of the intracellular protein Foxp3, the Live/Dead Fixable Blue Dead Cell Stain Kit (Molecular Probes/Thermo Fisher Scientific) was used to exclude dead cells. Data were analyzed using FlowJo software (Tree Star, Ashland, OR). The CD3-negative population, as determined by the staining of the isotype control Ab, included few CD4⁺/CD8⁺ cells.

Microarray Analysis of microRNAs

Total RNA was extracted from human BM-MSC- or NHDF-derived EVs using the miRNeasy Mini Kit (Qiagen, Hilden, Germany). The integrity of the RNA was evaluated using an Agilent 2100 Bioanalyzer (Agilent Technologies, Santa Clara, CA). The extracted total RNA was labeled with Cyanine5 using the 3D-Gene miRNA labeling kit (Toray Industries, Kamakura, Japan). The microRNA expression profiles were examined using the 3D-Gene miRNA microarray analysis system (Toray Industries). The mRNA targets of microRNAs were predicted using TargetScan (<http://www.targetscan.org/>). Gene Ontology (GO) enrichment and Kyoto Encyclopedia of Genes and Genomes (KEGG) pathway analyses were performed using GeneCodis tools with the predicted targets of each microRNA as the input (<http://genecodis.cnb.csic.es/>). The complete microarray data are available in the NCBI Gene Expression Omnibus. The microarray accession number is GSE99082.

Array Analysis of Soluble Factors

Soluble factors expressed by human BM-MSC- or NHDF-derived EVs were analyzed using the Proteome Profiler Human Cytokine Array (R&D Systems, Minneapolis, MN) according to the manufacturer's instructions. EVs were solubilized in Tween 20 (MP Biochemicals, Illkirch-Graffenstaden, France) at a final concentration of 1% and sonicated for 60 seconds. Protein prepared from EVs (300 μ g) was mixed with a cocktail of biotinylated detection antibodies and applied to membranes coated with immobilized capture antibodies. Immunoreactive proteins were detected and visualized with streptavidin-horseradish peroxidase and chemiluminescent detection reagents. Protein expression levels were measured using Quantity One software (Bio-Rad, Hercules, CA).

Statistical Analysis

Fisher's exact test was used unless otherwise indicated. Bar graphs indicate the mean \pm SD. Statistical significance is expressed as follows: *, $p < .05$; **, $p < .01$. Survival was estimated using the Kaplan–Meier method, and survival estimates were compared by log-rank testing. Statistical analyses were performed with the EZR software program [32].

RESULTS

Characteristics of EVs and Their Originated Human BM-MSCs

An overview of EV preparation from culture supernatants of human BM-MSCs is shown in Supporting Information Fig. S1A. EVs from three different lots of BM-MSCs expressed the EV-associated markers CD63 and CD81 by immunoblot analysis (Supporting Information Fig. S1B). Transmission electron microscopy of the prepared EVs identified particles with a

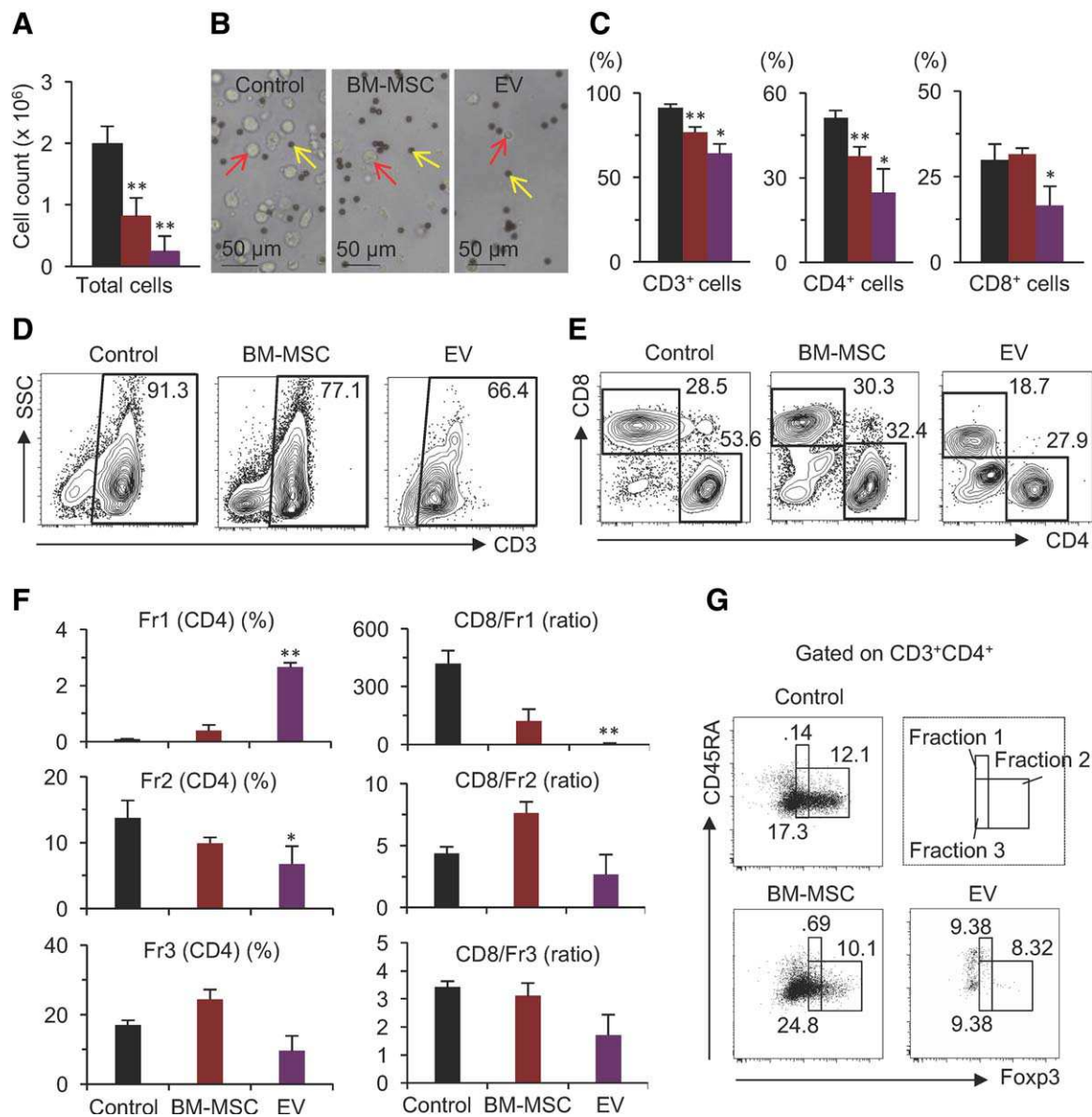


Figure 1. Human BM-MSC-derived EVs suppress T cells and preserve naive Treg in vitro. Human peripheral blood mononuclear cells (PBMCs) were activated with anti-CD3/CD28-coated Human T-Activator Dynabeads. These cells were cultured alone (black bars in A, C, F; Control in B, D, E, G), co-cultured with BM-MSCs (red bars in A, C, F; BM-MSC in B, D, E, G), or cultured with BM-MSC-derived EVs (purple bars in A, C, F; EV in B, D, E, G). (A): The number of viable cells was counted by Trypan blue dye exclusion. (B): Representative phase-contrast images of the cultures. Red arrows indicate PBMCs. Yellow arrows indicate Dynabeads. Bars, 50 μ m. Original magnification, $\times 200$. (C): Flow cytometric analysis showing the percentage of CD3⁺ T cells and the percentages of CD4⁺ and CD8⁺ T cells out of total CD3⁺ T cells. (D, E): Representative contour plots are shown. The numbers represent the percentage of CD3⁺ T cells or the percentages of CD4⁺ and CD8⁺ T cells out of total CD3⁺ T cells. The CD3-negative cell population, as determined by staining with isotype control antibodies, included few T cells (CD4⁺ or CD8⁺). (F, G): Flow cytometric analysis of three fractions of Fop3-expressing cells, Fraction 1 (Fr1; CD45RA⁺Fop3^{low} naive Treg), Fraction 2 (Fr2; CD45RA⁺Fop3^{high} activated Treg), and Fraction 3 (Fr3; CD45RA⁺Fop3^{low} non-Treg). (F) The frequency of each Fop3-expressing cell fraction out of total CD4⁺ T cells and the ratio of CD8⁺ T cells to each Fop3-expressing cell fraction are shown. (G) Representative contour plots are shown. The numbers indicate the percentage of each fraction out of all CD4⁺ T cells. Data in (A, C, F) represent the mean \pm SD. **, $p < .01$; *, $p < .05$. Abbreviations: BM-MSC, bone marrow mesenchymal stromal/stem cell; EVs, extracellular vesicles; SSC, side scatter.

saucer-like morphology, as previously described [33, 34] (Supporting Information Fig. S1C). The size of the particles in the EV preparations ranged from 90 to 400 nm, with most particles measuring approximately 110 nm (Supporting Information Fig. S1D).

When human PBMCs were stimulated with anti-CD3 and anti-CD28 antibodies in the presence of human BM-MSCs, the

number of expanded cells at 5 days was significantly lower than in cultures of PBMCs stimulated alone (Fig. 1A, 1B). Flow cytometric analysis showed that the expansion of total T cells as well as CD4⁺ T cells was substantially suppressed (Fig. 1C–1E). This suppressive effect was also observed when activated PBMCs were co-cultured with different lots of BM-MSCs and when a different lot of activated PBMCs was co-cultured with

the BM-MSCs (Supporting Information Fig. S2A, 2B). The PBMCs and MSCs were mismatched by at least six out of eight human leukocyte antigen (HLA) alleles (Supporting Information Table S2). Therefore, BM-MSC lots used in this study could suppress the expansion of T cells in an HLA-independent manner, as previously demonstrated [6, 35].

Human BM-MSC-Derived EVs Suppress the Expansion of Effector T Cells but Preserve Naive Regulatory T Cells In Vitro

The effect of EVs on the expansion of functional T cell subsets was evaluated in cultures of anti-CD3/CD28-stimulated PBMCs. In the presence of human BM-MSC-derived EVs, the expansion of anti-CD3/CD28-stimulated human PBMCs was suppressed (Fig. 1A, 1B). The expansion of total T cells, including CD4⁺ T cells, was suppressed in a manner similar to co-cultures with BM-MSCs (Fig. 1C–1E). The expansion of CD8⁺ T cells was also suppressed in the presence of EVs, but not in co-cultures with BM-MSCs (Fig. 1C–1E). When the supernatant fraction generated in the process of EV preparation was used instead of EVs in the expansion cultures, these suppressive effects were not observed (Supporting Information Fig. S1A, 1E, 1F). The EV-mediated suppressive effects were observed when anti-CD3/CD28-stimulated PBMCs were cultured in the presence of different lots of BM-MSC-derived EVs (Supporting Information Fig. S2A), and when different lots of PBMCs were cultured in the presence of BM-MSC-derived EVs (Supporting Information Fig. S2B).

Previous studies suggested that regulatory T cells (Treg) may be associated with the immunomodulatory functions of BM-MSCs [6]. We therefore examined whether BM-MSC-derived EVs influence Treg. In the anti-CD3/CD28-stimulated PBMC expansion cultures, the frequency of CD45RA⁺ Foxp3^{low} naive Treg (Fraction 1) was higher, and the frequency of CD45RA-Foxp3^{high} effector Treg (Fraction 2) was lower, in the presence of EVs (Fig. 1F, 1G). In addition, the ratio of total CD8⁺ T cells to naive Treg was lower in the presence of EVs (Fig. 1F, 1G). Finally, the frequency of CD45RA-Foxp3^{low} non-Treg (Fraction 3) was lower in cultures with EVs compared to cultures of PBMCs alone, suggesting the suppression of non-Treg within the Foxp3-expressing T cell population by BM-MSC-derived EVs. Collectively, these data demonstrate that BM-MSC-derived EVs preserve naive Treg.

With regard to other hematopoietic cell populations, the frequency of CD19⁺ cells, CD3-CD56⁺ cells, CD3-CD16⁺ cells, CD11b⁺ cells, and CD3-CD4^{dim} cells remained high in the expansion cultures of PBMCs containing EVs (Supporting Information Fig. S3). These results suggested that EVs specifically suppress the expansion of T cells, but not B cells, NK cells, or mature myeloid cell populations. In particular, B cells and mature myeloid cell populations seemed to be preserved in the expansion cultures with EVs (Supporting Information Fig. S3).

Human BM-MSC-Derived EVs Ameliorate the Clinical and Pathological Characteristics of Acute GVHD in Mice

To investigate the effects of BM-MSC-derived EVs on acute GVHD in vivo, a major histocompatibility complex (MHC)-haploidentical murine model was used in which 1×10^7 spleen cells from C57BL/6 mice (B6, H-2D^b) were injected into B6D2F1 (BDF1, H-2D^{bxd}) mice. These mice were randomly divided into two groups 5 days after the injection of spleen

cells. One group of GVHD mice was treated with human BM-MSC-derived EVs, and the other group of mice received saline injections (Fig. 2A). GVHD mice that received systemic infusion of EVs showed prolonged survival, with a median survival of 16 days compared with 10 days in the control GVHD mice (Fig. 2B). The clinical scores of EV-treated mice were lower than those of the control mice (average of 2.8 vs. 3.5, Fig. 2C), indicating that EVs ameliorated the systemic symptoms of acute GVHD such as body weight loss. EV treatment also significantly mitigated GVHD-associated pathology in the large bowel, particularly the infiltration of the lamina propria by inflammatory cells and the vacuolization and attenuation of surface colonocytes (Fig. 2D–2F). The histological scores of the livers of the EV-treated GVHD mice were lower than those of the control mice, but this did not reach statistical significance, and the histological scores of the small bowels of the EV-treated mice were comparable to those of the control mice (Fig. 2D, Supporting Information Fig. S4B; Supporting Information Table S3). With regard to the skin, the percentage of mice with severe damage was lower in the EV-treated group than in the control group (60.0% vs. 88.8%) (Fig. 2G, Supporting Information Fig. S4B; Supporting Information Table S4). Collectively, systemic administration of human BM-MSC-derived EVs significantly prolonged the survival of mice with acute GVHD, which was accompanied by an amelioration of clinical GVHD symptoms and pathological damage in multiple GVHD-targeted organs, particularly the large bowel.

Human BM-MSC-Derived EVs Suppress the Functional Differentiation of T Cells in Mice with GVHD

PB T cell subsets were analyzed in GVHD mice that received systemic administration of EVs. Flow cytometric analysis indicated that the expansion of CD8⁺ T cells was suppressed by treatment with human BM-MSC-derived EVs (Fig. 3A, 3B). In the control GVHD mice, most of the CD8⁺ and CD4⁺ T cells were CD62L-CD44⁺ effector T cells (Fig. 3C, Supporting Information Fig. S5B, 5D). In GVHD mice treated with EVs, the frequency and number of effector T cells among CD4⁺ and CD8⁺ T cells were decreased, and conversely, the frequency and number of CD62L⁺ CD44⁻ naive T cells were increased (Fig. 3C, Supporting Information Fig. S5A–5D). These results suggest that systemic administration of human BM-MSC-derived EVs suppressed the functional differentiation of T cells from a naive phenotype to an effector phenotype. The frequency of CD4⁺ CD25⁺ Foxp3⁺ Treg was also decreased in the GVHD control mice compared to mice without GVHD, whereas the EV-treated GVHD mice contained a substantial CD4⁺ CD25⁺ Foxp3⁺ population (Fig. 3D), suggesting that human BM-MSC-derived EVs preserve Treg.

The populations of non-T cells, including CD19⁺ Gr-1⁻ cells (B cells), Gr-1-CD11b⁺ cells (monocytes), and Gr-1⁺ CD11b⁺ cells (neutrophils), were depleted in the control GVHD mice compared to mice without GVHD, but EV treatment ameliorated the depletion of these cell populations (Supporting Information Fig. S6).

NHDF-Derived EVs Do Not Suppress T Cell Expansion In Vitro or Ameliorate Acute GVHD in Mice

We explored whether the anti-GVHD effects of BM-MSC-derived EVs could be induced by EVs derived from other stromal cells. To address this, we used NHDFs because they are adherent stromal cells with a similar morphology to human BM-MSCs.

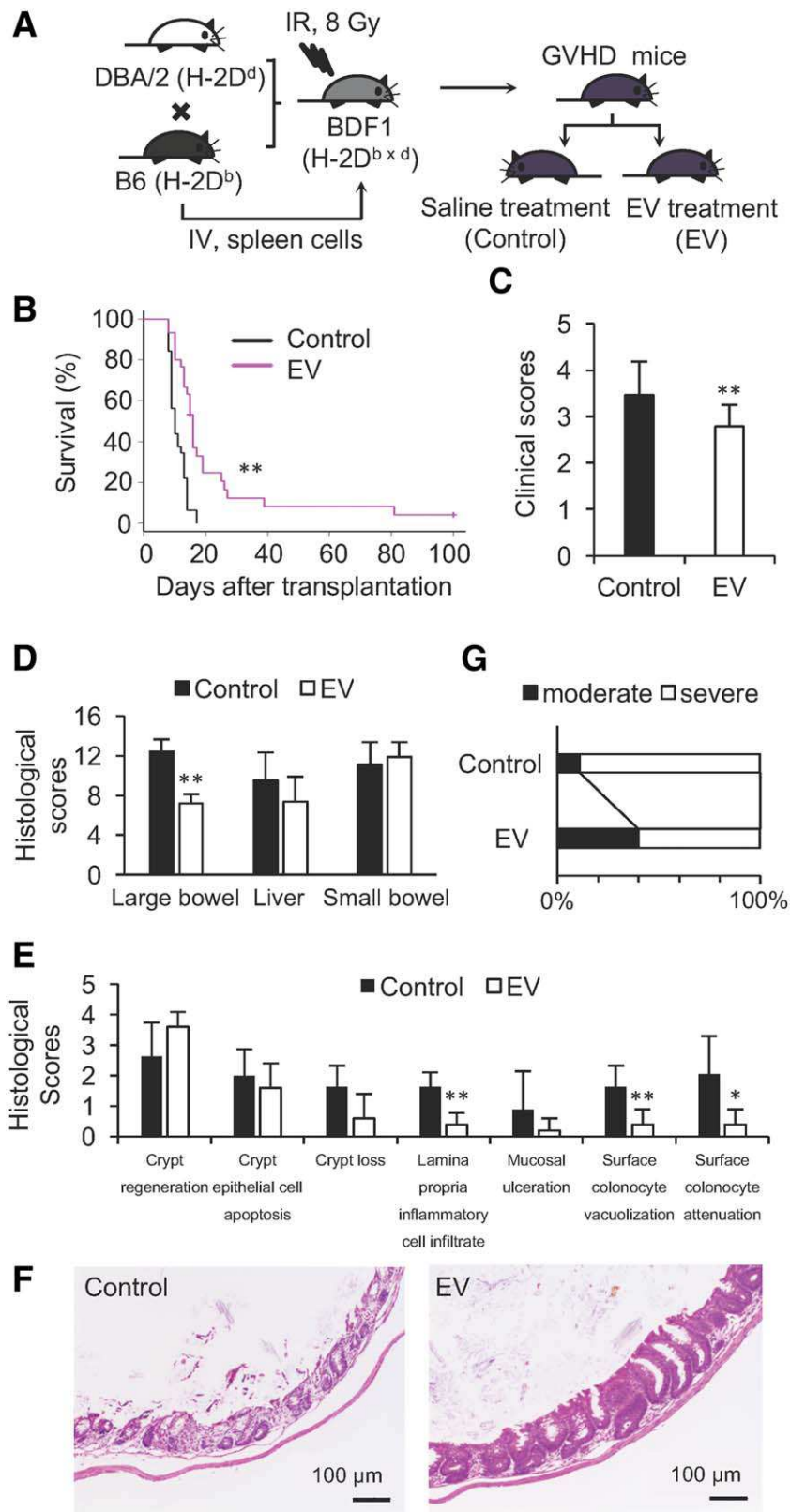


Figure 2. Human bone marrow mesenchymal stromal/stem cell (BM-MSC)-derived EVs ameliorate the clinical and pathological characteristics of GVHD in mice. **(A):** Schema of the EV treatment study. IR, irradiation; IV, intravenous infusion. **(B):** Survival curves of the GVHD mice that received human BM-MSC-derived EVs (EV, red line) or saline (Control, black line). The survival of the mice was observed until day 100 and plotted as a Kaplan–Meier curve ($n = 30$ for EV-treated GVHD mice; $n = 32$ for control GVHD mice). **, $p < .01$. **(C):** Clinical scores of the GVHD mice 10 days after the injection of spleen cells. Scores from five GVHD-associated parameters were summed, from 0 to 10 ($n = 28$ for EV-treated GVHD mice; $n = 18$ for control GVHD mice). **(D):** Histological scores of the GVHD mice. Scores from multiple GVHD-associated parameters were summed, from 0 to 28 for the large bowel and small bowel and from 0 to 40 for the liver ($n = 5$ for EV-treated GVHD mice; $n = 8$ for control GVHD mice). **(E):** Histological scores of seven parameters in the large bowel. **(F):** Representative microscopic images of H&E-stained sections of large bowel specimens from the mice. Bars, 100 μm. Original magnification, $\times 100$. White and black bars in (C–E) indicate the scores of GVHD mice that received BM-MSC-derived EVs (EV) or saline (Control). **(G):** Histological evaluation of skin specimens from the GVHD mice. The percentage of mice whose severity of damage was evaluated as moderate (black) or severe (white) is shown ($n = 5$ for EV-treated GVHD mice; $n = 9$ for control GVHD mice). In (D, E, G), the scores were assessed 6 days after the administration of EVs. Data in (C–E) indicate the mean \pm SD. **, $p < .01$; *, $p < .05$. Abbreviations: EVs, extracellular vesicles; GVHD, graft-versus-host disease.

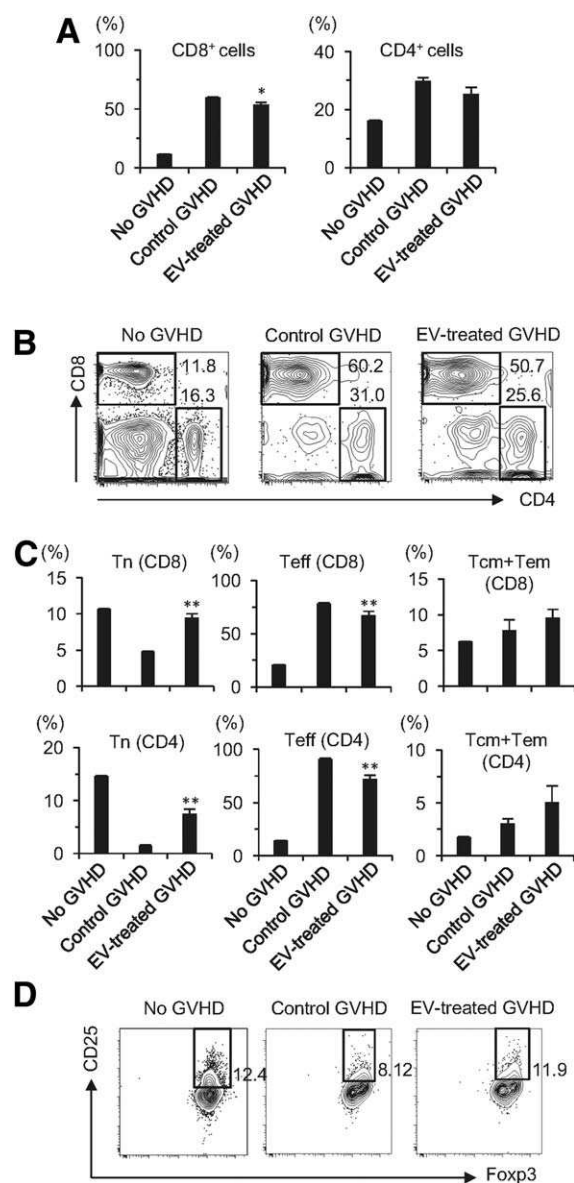


Figure 3. Human bone marrow mesenchymal stromal/stem cell (BM-MSC)-derived EVs preserve peripheral naive T cells and Treg in mice with GVHD. Flow cytometric analysis of T cell subsets in PB from the GVHD mice 6 days after the administration of EVs. **(A):** The frequency of CD8⁺ and CD4⁺ T cells. **(B):** Representative contour plots are shown. **(C):** The frequency of naive (Tn; CD62L+CD44⁻), effector (Teff; CD62L-CD44⁺), and central memory and effector memory (Tcm and Tem; CD62L+CD44⁺) T cells out of total CD8⁺ and CD4⁺ T cells. **(D):** Flow cytometric analysis of Treg. The numbers indicate the percentage of Treg out of total CD4⁺ T cells in the PB. No GVHD, BDF1 mice that did not receive spleen cells from B6 mice; Control GVHD, BDF1 mice that received spleen cells from B6 mice (H-2D^b) but did not receive human BM-MSC-derived EVs; EV-treated GVHD, BDF1 mice that received spleen cells from B6 mice and then received human BM-MSC-derived EVs. Data in (A, C) indicate the mean \pm SD. **, $p < .01$; *, $p < .05$. Abbreviations: EVs, extracellular vesicles; GVHD, graft-versus-host disease.

Flow cytometric analysis showed that NHDFs were negative for hematopoietic and endothelial markers, including CD45, CD34, CD11b, CD19, CD31, and HLA-DR, and were positive for mesenchymal stem cell-associated markers, including CD105, CD73,

CD90, CD44, and CD166, which was a similar expression pattern as BM-MSCs (Supporting Information Fig. S7A, 7B). On the other hand, NHDFs were distinct from BM-MSCs in the expression of CD10, CD106, and CD146 (Supporting Information Fig. S8A). In addition, NHDFs did not show apparent multi-differentiation capability to osteogenic (Supporting Information Fig. S8B, 8C), chondrogenic (Supporting Information Fig. S8D), or adipogenic (Supporting Information Fig. S8E, 8F) cells in vitro. Moreover, unlike BM-MSCs, NHDFs did not form bone or induce hematopoietic marrow when subcutaneously transplanted into immunocompromised mice (Supporting Information Fig. S8G). Thus, NHDFs were fundamentally different from BM-MSCs.

When anti-CD3/CD28-stimulated human PBMCs were cultured with NHDF-derived EVs, the expansion of total T cells, including CD4⁺ and CD8⁺ T cells, was comparable to that in cultures of PBMCs alone and in cultures with the supernatant fraction generated in the process of EV preparation from conditioned SFM of NHDFs (Supporting Information Fig. S9A, 9B). Therefore, NHDF-derived EVs did not have the suppressive effects on T cells seen with BM-MSC-derived EVs.

In accordance with these observations, when MHC-haploidentical GVHD mice received NHDF-derived EVs, the survival of the mice was not prolonged and was actually shortened compared to the control mice (Supporting Information Fig. S10A). The clinical scores of the GVHD mice treated with NHDF-derived EVs were comparable to those of the control GVHD mice (Supporting Information Fig. S10B). In addition, the histological scores for the large bowel, liver, and small bowel of GVHD mice treated with NHDF-derived EVs were comparable to those of the control GVHD mice (Supporting Information Fig. S10C). With regard to the skin, in the mice treated with NHDF-derived EVs, the percentage of mice with severely damaged skin was lower, and conversely, the percentage of mice with mildly or moderately damaged skin was higher compared to the control mice (Supporting Information Fig. S10D). Flow cytometric analysis of PB T cell subsets in GVHD mice indicated that the expansion of CD8⁺ T cells was not suppressed by treatment with NHDF-derived EVs (Supporting Information Fig. S10E). In addition, the frequency of effector T cells, naive T cells, and Treg in GVHD mice treated with NHDF-EVs was comparable to that in the control GVHD mice (Supporting Information Fig. S10E, 10F). Collectively, these data indicate that systemic administration of NHDF-derived EVs had no significant effect on the functional differentiation of T cells from a naive phenotype to an effector phenotype or on the preservation of Treg. These data suggest that the immunologic and anti-GVHD effects of human BM-MSC-derived EVs are unique, at least in comparison to NHDF-derived EVs.

Proliferation-Related Gene Signatures Are Downregulated by microRNAs in Human BM-MSC-Derived EVs

The expression of multiple soluble factors such as cytokines, chemokines, and growth factors in NHDF-derived and BM-MSC-derived EVs was compared (Supporting Information Fig. S11). Differences in the expression of several molecules, including macrophage migration inhibiting factor, interleukin (IL)-13, plasminogen activator inhibitor-1, and CXCL12, were observed.

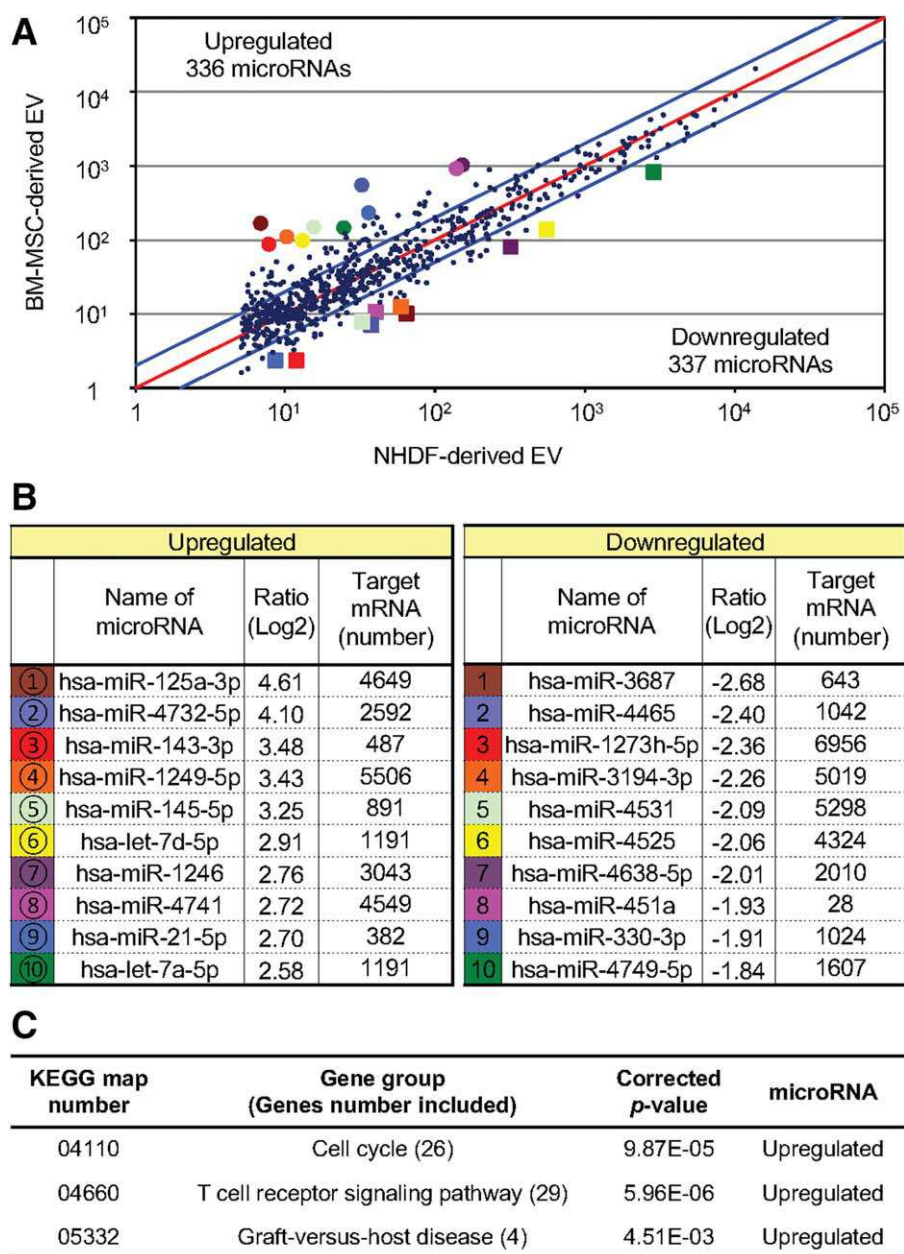


Figure 4. Microarray analysis of microRNAs in BM-MSC-derived EVs versus NHDF-derived EVs. **(A):** Scatter plot of microRNAs expressed in BM-MSC-derived EVs compared with NHDF-derived EVs. Blue lines indicate the 2.0-fold threshold. Circles represent the top 10 upregulated microRNAs in BM-MSC-derived EVs. Squares represent the top 10 downregulated microRNAs in BM-MSC-derived EVs. **(B):** List of the top 10 microRNAs that were up- or downregulated in BM-MSC-derived EVs. The color of the numbers corresponds to the color of the circles or squares in the scatter plot in (A). **(C):** Kyoto Encyclopedia of Genes and Genomes pathway analysis of mRNAs that were commonly targeted by three or more microRNAs among the top 10 up- or downregulated microRNAs. Abbreviations: BM-MSC, bone marrow mesenchymal stromal/stem cell; EVs, extracellular vesicles; NHDF, normal human dermal fibroblasts.

Finally, microarray analysis of microRNAs in BM-MSC-derived EVs was performed (Supporting Information Fig. S12). This analysis identified 336 and 337 microRNAs that were upregulated or downregulated, respectively, in human BM-MSC-derived EVs compared to NHDF-derived EVs (Fig. 4A, Supporting Information S-File 1). Among them, miR-125a-3p was identified as the most highly upregulated microRNA in BM-MSC-derived EVs (Fig. 4B). TargetScan analysis predicted 11726 mRNAs as targets of the top 10 upregulated microRNAs (Supporting Information S-File 2). Among them, 3477 mRNAs

were commonly targeted by three or more microRNAs and were selected for further analysis. GO enrichment analysis showed that these commonly targeted genes were highly involved in the regulation of proliferation-related processes (Table 1). A similar analysis was performed on 12553 mRNAs that were predicted as targets of the top 10 downregulated microRNAs (Fig. 4B, Supporting Information S-File 3). Among them, 4356 mRNAs were commonly targeted by three or more microRNAs, and these mRNAs were found to be highly involved in inhibition of proliferation by GO enrichment

Table 1. List of enriched GO terms. GO analysis of commonly targeted genes by up- or downregulated microRNAs in bone marrow mesenchymal stromal/stem cell-derived extracellular vesicles

| GO accession | GO term (number of genes included) | Corrected <i>p</i> -value | microRNA |
|--------------|--|---------------------------|---------------|
| 0008284 | Positive regulation of cell proliferation (93) | 4.20 E −16 | Upregulated |
| 0008285 | Negative regulation of cell proliferation (86) | 2.28 E −09 | Downregulated |
| 0007049 | Cell cycle (79) | 2.49 E −06 | Upregulated |
| 0008283 | Cell proliferation (64) | 5.82 E −07 | Upregulated |
| 0051301 | Cell division (47) | 2.11 E −03 | Upregulated |
| 0000278 | Mitotic cell cycle (43) | 1.39 E −02 | Upregulated |
| 0000082 | G1/S transition of mitotic cell cycle (29) | 1.49 E −03 | Upregulated |
| 0007067 | Mitosis (29) | 1.42 E −02 | Upregulated |
| 0007050 | Cell cycle arrest (28) | 6.70 E −03 | Downregulated |
| 0030307 | Positive regulation of cell growth (13) | 6.91 E −03 | Upregulated |
| 0051781 | Positive regulation of cell division (13) | 2.43 E −03 | Upregulated |
| 0045786 | Negative regulation of cell cycle (11) | 1.48 E −02 | Downregulated |
| 0045787 | Positive regulation of cell cycle (8) | 8.83 E −03 | Upregulated |
| 0045930 | Negative regulation of mitotic cell cycle (5) | 4.67 E −02 | Downregulated |
| 0071158 | Positive regulation of cell cycle arrest (5) | 3.04 E −02 | Downregulated |

Abbreviation: GO, Gene Ontology.

analysis (Table 1). Collectively, these analyses suggest that microRNAs within BM-MSC-derived EVs downregulate cell proliferation. Furthermore, KEGG pathway analysis identified gene groups involved in cell cycle regulation, T cell receptor signaling, and GVHD (Fig. 4C). These pathways were considered to be downregulated because they include genes targeted by commonly upregulated microRNAs.

DISCUSSION

A series of clinical studies have examined the efficacy of systemic infusion of culture-expanded BM-MSCs for acute GVHD patients and shown overall response rates ranging from about 30%–80% [36, 37]. Attempts to improve the outcome of BM-MSC therapy have been based on the concept that this form of therapy is dependent on the number of infused cells that can successfully traffic to sites of damaged or diseased tissue [38]. However, systemic administration of an increased number of cells did not augment the therapeutic effects of BM-MSCs in GVHD [39]. In addition, another approach, in which BM-MSCs were directly delivered into the gut via the mesenteric artery, was not more effective than systemic injection [40]. These clinical results underscore the current molecular understanding that the therapeutic effects of BM-MSCs are, at least in acute GVHD, attributed mainly to secreted immune-modulatory factors [9, 41]. In the present study, we found, for the first time, that human BM-MSC-derived EVs ameliorated GVHD symptoms and pathology in GVHD-targeted organs, and prolonged the survival of GVHD mice in association with preservation of circulating naive T cell populations.

BM-MSCs suppress the expansion of human naive T cells as well as activated CD4+ and CD8+ T cells regardless of MHC compatibility [41, 42]. It has also been reported that BM-MSCs induce human Treg, which inhibit allogeneic lymphocyte proliferation [43, 44]. In line with these reports, we found that BM-MSC-derived EVs suppressed the proliferation of CD4+ and CD8+ T cells in anti-CD3/CD28-stimulated expansion cultures of human PBMCs and in PB obtained from the GVHD mice. In addition, BM-MSC-derived EVs suppressed the functional differentiation of T cells from a naive to an

effector phenotype in the GVHD mice. Moreover, naive Treg were preserved in the presence of BM-MSC-derived EVs in cultures of anti-CD3/CD28-stimulated human PBMCs and in PB of the GVHD mice. Collectively, it is conceivable that the anti-GVHD effect of BM-MSCs is, at least partially, associated with an EV-mediated immunomodulatory effect on T cells.

However, a number of studies suggest that MSC-derived EVs mimic the therapeutic effects of their MSCs of their origin to a large extent, even though the underlying mechanisms may not necessarily be similar [13]. In our in vitro study, BM-MSCs suppressed the expansion of CD3+ T cells to a lesser extent than EVs derived from the same number of the BM-MSCs from which they originated. BM-MSC-derived EVs may, therefore, have a stronger effect on T cell suppression than BM-MSCs. This is supported by the observation that the suppressive effect of EVs on T cell expansion was dose-dependent (data not shown). With respect to the Foxp3-expressing T cell population, the suppression of CD45RA-Foxp3^{low} cells (non-Treg) by BM-MSC-derived EVs might reflect the suppression of activated CD4+ T cells. Given that CD45RA + Foxp3^{low} naive Treg become CD45RA-Foxp3^{high} Treg upon anti-CD3/CD28 stimulation, it is possible that BM-MSC-derived EVs had the enhanced suppressive effect on the ability of Treg to shift from a naive to an activated status or that BM-MSC-derived EVs induced more naive Treg within the CD4+ T cell population compared to BM-MSCs. Previous in vitro studies on the modulation of functional T cell populations by BM-MSCs have been contradictory [45–47]. As for in vivo studies, a recent report suggested that EVs contribute to the suppression of Th1 cells in a human-to-mouse xenogeneic chronic GVHD model [48]. Further studies are needed to determine the contribution of EVs to the BM-MSC-mediated T cell modulation.

Various types of cells release EVs. To address the unique effects of human BM-MSC-derived EVs, we used NHDF-derived EVs as a control because human BM-MSCs and fibroblasts share many properties, including a plastic-adherent spindle-like morphology and a similar surface marker expression profile [49]. Nevertheless, NHDFs are functionally different from BM-MSCs. In our analysis, NHDFs lacked multi-differentiation capacity and hematopoiesis induction. In addition, NHDF-derived EVs did not suppress T cell expansion

in cultures with anti-CD3/CD28-stimulated PBMCs. Most importantly, NHDF-derived EVs did not exhibit the anti-GVHD effects of BM-MSC-derived EVs, including amelioration of clinical symptoms, resolution of the pathology in the gut and liver, or prolongation of survival. These results suggest that BM-MSC-derived EVs have a unique therapeutic effect in acute GVHD. Interestingly, systemic infusion of human BM-MSC-derived EVs was effective in resolving the pathology in the large bowel and skin of the GVHD mice. This is consistent with the clinical characteristics of BM-MSC therapy for acute GVHD [7, 8, 50, 51]. The mechanisms that underlie the differences in the efficacy of BM-MSC-derived EVs among organs/tissues have not been well-studied.

There are limitations to this study. First, the effects of BM-MSC-derived EVs on GVHD-targeted organs were modest. Only the suppression of GVHD pathology in the large intestine was significantly associated with clinical improvement in GVHD mice treated with BM-MSC-derived EVs. Although multiple organs can be affected in GVHD, pathologic damage to the large intestine can be lethal; therefore, favorable effects of BM-MSC-derived EVs on the large intestine might predominantly contribute to the improved clinical outcomes. Second, the survival of GVHD mice treated with NHDF-derived EVs was less than that of the control GVHD mice, despite the lack of effects on PB T cells. This suggests the possibility that the distribution of T cell subsets in the PB does not reflect the distribution in GVHD-targeted organs.

Comprehensive characterization of EVs would provide the information necessary to explore their therapeutic potential [52]. A previous study by Phinney et al. reported the microRNA expression profiles of MSC-derived exosomes [53]. Because they compared microRNA expression levels between exosomes and their parental MSCs, the most highly up- or downregulated microRNAs were different from the most highly regulated microRNAs in our analysis. However, it is of interest that such microRNAs in that study were also upregulated in EVs in our analysis. MicroRNAs that are expressed differentially in EVs compared with the parental MSCs might contribute to MSC-associated functions.

Microarray analysis of microRNAs in BM-MSC-derived EVs versus NHDF-derived EVs revealed the differential expression of multiple microRNAs, suggesting the involvement of multiple biological processes. Previous studies have demonstrated that BM-MSCs inhibit the proliferation of activated T cells via cell cycle arrest [54, 55] and modulate the expression of various cytokines, including proinflammatory (e.g., IL-2, IFN- γ , TNF- α) and anti-inflammatory cytokines (e.g., IL-4, IL-10), which play important roles in the pathogenesis of acute GVHD [6, 9, 56–59]. The GO enrichment analysis identified the downregulation of multiple cell proliferation-related processes but not altered production of these cytokines. Furthermore, KEGG analysis suggested the downregulation of pathways associated with GVHD and T cell receptor signaling. These comprehensive analyses support our *in vitro* and *in vivo* results, where T cell expansion was suppressed by BM-MSC-derived EVs and acute GVHD was suppressed clinically and pathologically in GVHD mice.

Of the microRNAs that were differentially expressed in human BM-MSC-derived EVs and NHDF-derived EVs, miR-125a-3p was the most highly altered microRNA. Notably, miR-125a-3p suppressed cell proliferation in several cell lines, consistent with our *in vitro* observations [60–62]. It has also been shown that miR-125a is downregulated in PBMCs from patients with systemic

lupus erythematosus [63]. The downregulation of miR-125a contributed to the elevated expression of the inflammatory chemokine regulated upon activation, normal T cell expressed and secreted by targeting Kruppel-like factor 13 in activated T cells [64]. Therefore, the upregulation of miR-125a-3p in BM-MSC-derived EVs might contribute to the suppression of T cells. Collino et al. performed microarray analysis of microRNAs contained in EVs released from both BM-MSCs and liver-resident stem cells [65]. Although miR-125a was not specifically discussed by the authors, it was one of the most abundantly expressed microRNAs in microvesicles and their cells of origin. Their analysis indicated that abundantly expressed microRNAs in BM-MSCs contributed to multiple cell processes, including regulation of the immune system, differentiation-related functions, and processes related to the regulation of cell cycle progression, proliferation, and cell death. One microRNA can regulate many target genes, while conversely one gene can be targeted by many microRNAs; thus multiple relationships between microRNAs and target genes elaborately determine the fate of T cells. It will be important to use a conditional microRNA-125a-3p knockout mouse model to more conclusively demonstrate the association between upregulated microRNA-125a-3p and the anti-GVHD effect.

Array analysis of multiple soluble factors identified several molecules that were more highly expressed in BM-MSC-derived EVs than in NHDF-derived EVs. Among them, CXCL12 could potentially be associated with the amelioration of GVHD, as was reported in a previous study [66]. EVs contain a variety of bioactive molecules, and further analysis of immune-modulatory factors is warranted to fully understand the anti-GVHD mechanism of BM-MSC-derived EVs.

Use of BM-MSC-derived EVs may have potential advantages over their cell of origin in some aspects. From a safety standpoint, concerns about the transformation of BM-MSCs to malignant cells in patients do not need to be considered with the use of EVs. From a therapeutic standpoint, BM-MSCs may become trapped in capillaries, particularly in the lungs, and become unable to reach damaged or diseased tissues/organs, which is necessary for them to exert their therapeutic effects. This is also not a concern with EVs. On the other hand, BM-MSCs are activated by proinflammatory cytokines present in the microenvironment of damaged or diseased tissues/organs [67]. This implies that the immunomodulatory effects of BM-MSCs might not be exerted in the absence of abnormal environmental conditions. Our study suggests that BM-MSC-derived EVs have therapeutic effects in acute GVHD. However, the EVs showed strong suppression of T cell activation *in vitro*, and extreme immunosuppression by BM-MSC-derived EVs may increase susceptibility to infection in a clinical setting. In addition, because EVs are small, spherical membrane fragments and may include exosomes, microvesicles, and apoptotic bodies [33], there is a possibility that the BM-MSC-derived EV-concentrated fractions in this study contain the above particles [68]. Therefore, additional research incorporating more homogenous EV preparations is warranted.

CONCLUSION

Human BM-MSC-derived EVs exerted immunomodulatory effects on T cells *in vitro* and anti-GVHD effects in mice. Amelioration of acute GVHD by BM-MSC-derived EVs was associated with the

preservation of circulating naive T cells. Microarray analysis identified microRNAs associated with the immunomodulatory effects of BM-MSC-derived EVs. Further studies are needed to increase the potency of BM-MSC-derived EVs and to better understand the mechanisms of action of this novel potential therapeutic for acute GVHD.

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AUTHOR CONTRIBUTIONS

S.F., A.F., T.S., and Y.S.: conception and design, collection of study material, collection and assembly of data, data analysis and interpretation, manuscript writing; Y.M.: conception and design, financial support, collection of study material, collection and assembly of data, data analysis and interpretation, manuscript writing; H.H.: conception and design, collection of study material, assembly of data, data analysis and interpretation, manuscript writing; H.T.: collection and assembly of data, data analysis and interpretation; A.T.-K., T.I., and T.M.: conception and design, financial support, administrative support, provision of study material, data analysis and interpretation, manuscript writing; S.F., A.F., T.S., Y.S., Y.M., H.H., H.T., A.T.-K., T.I., and T.M.: final approval of manuscript.

DISCLOSURE OF POTENTIAL CONFLICTS OF INTEREST

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